

# First 230 GHz VLBI Fringes on 3C 279 using the APEX Telescope

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## ABSTRACT

**Aims.** We report about a 230 GHz very long baseline interferometry (VLBI) fringe finder observation of blazar 3C 279 with the APEX telescope in Chile, the phased submillimeter array (SMA), and the SMT of the Arizona Radio Observatory (ARO).

**Methods.** We installed VLBI equipment and measured the APEX station position to 1 cm accuracy ( $1\sigma$ ). We then observed 3C 279 on 2012 May 7 in a 5 hour 230 GHz VLBI track with baseline lengths of 2800 M $\lambda$  to 7200 M $\lambda$  and a finest fringe spacing of 28.6  $\mu$ as.

**Results.** Fringes were detected on all baselines with SNRs of 12 to 55 in 420 s. The correlated flux density on the longest baseline was  $\sim 0.3$  Jy beam<sup>-1</sup>, out of a total flux density of 19.8 Jy. Visibility data suggest an emission region  $\lesssim 38$   $\mu$ as in size, and at least two components, possibly polarized. We find a lower limit of the brightness temperature of the inner jet region of about  $10^{10}$  K. Lastly, we find an upper limit of 20 % on the linear polarization fraction at a fringe spacing of  $\sim 38$   $\mu$ as.

**Conclusions.** With APEX the angular resolution of 230 GHz VLBI improves to 28.6  $\mu$ as. This allows one to resolve the last-photon ring around the Galactic Center black hole event horizon, expected to be 40  $\mu$ as in diameter, and probe radio jet launching at unprecedented resolution, down to a few gravitational radii in galaxies like M 87. To probe the structure in the inner parsecs of 3C 279 in detail, follow-up observations with APEX and five other mm-VLBI stations have been conducted (March 2013) and are being analyzed.

**Key words.** galaxies: individual (3C 279) – galaxies: jets – instrumentation: high angular resolution – telescopes

## 1. Introduction

Very long baseline interferometry (VLBI) at (sub)millimeter wavelengths offers the unique possibility of high angular resolution studies of objects that are self-absorbed or scatter broadened at longer wavelengths. For the nearby supermassive black holes (SMBH) in Sgr A\* and M 87 the angular resolution of global mm-VLBI approaches the diameter of the expected black hole shadow and photon ring size (e.g., Falcke et al. 2000; Riecke & Dexter 2015).

In this context a joint effort is being undertaken to build a global (sub)mm-VLBI array to image the immediate environment of nearby BHs. The angular resolution and imaging capabilities of this array, called the Event Horizon Telescope<sup>1</sup> (EHT; cf. Doleman et al. 2008, 2009), can be improved by adding more stations and longer baselines. As a part of such efforts we carried out a pilot mm-VLBI experiment with the 12 m APEX telescope<sup>2</sup> situated near the ALMA array at Chajnantor, Chile.

<sup>1</sup><http://www.eventhorizontelescope.org>

<sup>2</sup>This publication is based on data acquired with the Atacama Pathfinder Experiment (APEX). APEX is a collaboration between the

This pilot experiment could be regarded as a pathfinder for the planned participation of ALMA in mm-VLBI.

Two initial attempts at adding a southern mm-VLBI station did not produce fringes (ASTE in 2010 by Honma et al. (NAOJ), APEX in 2011). After improvements at APEX in 2012 (for technical details, see Roy et al. 2013), we detected the first 230 GHz fringes at extremely long baselines of 7170 km to 9450 km with the currently highest angular resolution of  $28.6 \mu\text{as}$ . This continuation of earlier efforts (e.g., Krichbaum et al. 2004, 2008) enables global 1.3 mm-VLBI at an angular resolution sufficient to resolve event horizon scale emission in Sgr A\* and M 87. These and several other sources will be observed over the next years.

## 2. Blazar 3C 279

The blazar 3C 279 is one of the brightest and best monitored flat-spectrum quasars and was the first object to exhibit apparent superluminal motion. The source of its strong radio to  $\gamma$ -ray emission is a relativistic jet of material ejected from near the black hole in 3C 279. The southwest oriented large-scale jet has been extensively studied with  $\leq 86$  GHz VLBI. Adopting the black hole mass of Nilsson et al. (2009), the redshift of Marziani et al. (1996), and  $\Lambda$ CDM cosmology of Hinshaw et al. (2013), the scale on 3C 279 is  $1.0 \mu\text{as} \cong 0.0064 \text{ pc} \cong 130 R_s$ .

As one of the brightest quasars 3C 279 is suitable for VLBI fringe finding, although its structure is partially resolved at mm wavelengths. An observation at 147 GHz finds a single  $34 \mu\text{as}$  component (but is limited by uv coverage; cf. Krichbaum et al. 2002), whereas 43 GHz VLBI data from the VLBA-BU-BLAZAR project (Jorstad et al. 2011) suggest three components in the inner 1 mas. Similarly, in a 230 GHz EHT observation in 2011 one to two components are seen offset from the core by 80–145  $\mu\text{as}$  (Lu et al. 2013).

## 3. APEX Station Position

A high-precision APEX station position is required to minimize the residual fringe rate that causes coherence loss during time integration in the VLBI correlator. Maintaining better than 90 % coherence in 1 s requires the residual fringe rate to be  $< 0.25$  Hz. At 345 GHz this corresponds to a position error of  $< 3$  m.

We derived an initial low-accuracy position (3 m rms) using a single-band TrueTime XL-AK GPS timing receiver mounted on the telescope, and data logged in 2010 over a one-month period. For better accuracy Onsala later supplied a dual-band Ashtech Micro-Z GPS receiver and TIGO in Concepción lent a choke-ring antenna. We logged dual-band GPS data of the telescope azimuth track over several days in March 2011. Kinematic position solutions were derived to determine the circle center, giving the position of the azimuth axis with 0.3 mm accuracy. These were adjusted upward by  $46 \pm 0.5$  cm, which is the altitude difference between the reference plane of the GPS antenna and the telescope elevation axis.

The final single- and dual-band GPS station positions agreed to 20 cm, well within their error bounds. The resulting position of the axis intersection, accurate to 1 cm ( $1\sigma$ ), is provided below as Geodetic and X, Y, Z coordinates in the ITRF2005 system:

Lat.	$23^\circ 00' 20.8037''\text{S}$	X	2225039.5297 m
Lon.	$67^\circ 45' 32.9035''\text{W}$	Y	-5441197.6292 m
Alt.	5104.47 m	Z	-2479303.3597 m

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Table 1: Baseline resolution and attained sensitivity

Baseline	B (km)	B (M $\lambda$ )	$\theta_B$ ( $\mu\text{as}$ )	Obs. time (hours)	$dS_{230}$ (mJy)
SMT–SMA	4627	$\approx 3200$	58.4	1.75	0.07
APEX–SMT	7174	$\approx 5400$	37.7	2.33	0.18
SMA–APEX	9447	$\approx 6800$	28.6	1.75	0.08

**Notes.**  $\theta_B$ : fringe spacing.  $dS_{230}$ : median attained sensitivity ( $1\sigma$ ) over a 480 MHz bandwidth in 10 s, the shortest atmospheric coherence time.

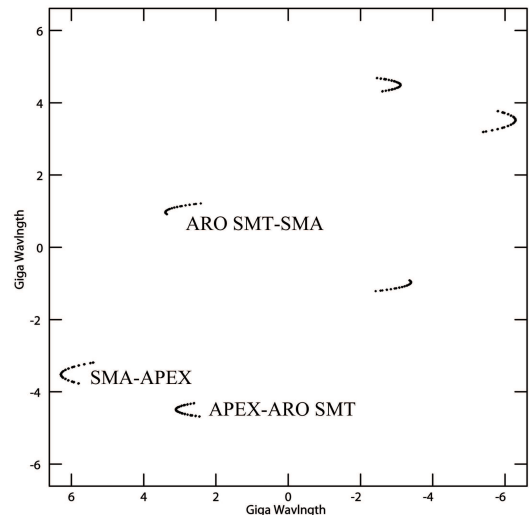


Fig. 1: UV coverage on 3C 279 on 2012 May 7 UT 02:00-07:00.

## 4. Observation

We observed 3C 279 in a three-station 230 GHz (1.3 mm) VLBI session on 2012 May 7 from UT 02:00 to 06:52 during good mm-VLBI weather. The three stations were: 1) the 12 meter APEX telescope jointly operated by the MPIfR, ESO and OSO on the Chajnantor plateau in Atacama, Chile (see Güsten et al. 2006), close to the ALMA array, 2) the Arizona Radio Observatory (ARO) -operated 10 meter Heinrich Hertz Sub-millimeter Telescope (ARO SMT) on Mount Graham, Arizona, and 3) the Submillimeter Array (SMA; CfA and ASIAA) on Mauna Kea, Hawaii, with eight 6 meter dishes phased. The SMA joined the observation at UT 03:15. The observation sampled a 512 MHz bandwidth (480 MHz usable) in lower sideband at 229.33 GHz using DBE1 polyphase filterbank backends (cf. Digital Backend Memo Series, MIT Haystack). At APEX a second backend was installed, the DBBC (Tuccari et al. 2012). Data were recorded at 2 Gbit/s on Mark 5 recorders.

The three VLBI baselines (Table 1) sampled uv radii of 2800  $M\lambda$  to 7200  $M\lambda$ . The shortest fringe spacing was  $28.6 \mu\text{as}$ . The uv coverage on 3C 279 is shown in Fig. 1.

### 4.1. Polarization

The ARO SMT recorded both circular polarizations. At APEX we used the 230 GHz single-polarization APEX-1 SHeFI receiver (see Belitsky et al. 2007; Vassilev et al. 2008) and inserted a  $\lambda/4$  plate into the optical path to convert linear into circular polarization. The native APEX handedness after 9 mirror reflections (Wieching 2010, private comm.) was LCP (“L”). To maximize experiment output, we switched APEX to RCP (“R”) at UT 04:30 by reorienting the  $\lambda/4$  plate. Lastly, the SMA unin-

Table 2: Station amplitude calibration data.

Station	$\tau_0$	$T_{\text{sys}}$ (K)	Gain (K/Jy)	SEFD (Jy)
APEX	0.06–0.09	180 (170–185)	0.0281	6410
SMT	0.21–0.33	250 (230–300)	0.0182	13740
SMA	0.03–0.06	95 (85–125)	0.0445	2130

**Notes.** Atmospheric opacities,  $\tau_0$ , were measured with water vapor radiometers. System temperatures,  $T_{\text{sys}}$ , are double-sideband for ARO SMT, and an antenna average for the SMA.

tentionally observed in a single linear polarization (“X”), thus complicating the interpretation of the resultant visibilities.

#### 4.2. Receiver Coherence at APEX

We monitored the APEX receiver coherence by injecting an H-maser -locked 229 GHz pilot tone (PCal) into the SHeFI receiver optics via a horn antenna. The PCal system increased the system temperature negligibly and did not change the nominal APEX sensitivity. The PCal tone phase was measured in 2012, 2013, and again in 2015 with a better tone synthesizer. The receiver coherence ( $> 95\%$  in 1 s) met the requirements for mm-VLBI.

#### 5. Data reduction

The station recordings were correlated at the MPIfR Bonn in the DiFX software correlator (Deller et al. 2011). We fringe fitted and reduced the visibility data in NRAO AIPS using standard methods. As a cross-check we also reduced the data in the Haystack Observatory Postprocessing System<sup>3</sup> for mm-VLBI (HOPS; cf. Lonsdale & Doeleman 1998), with consistent results.

Calibrations included antenna system temperature data, and a gain calibration on the Moon and Saturn, with a gain estimate used for the phased SMA. Water vapor radiometer and sky dip data were used to correct for atmospheric opacity at a slow cadence. These a priori calibration data are summarized in Table 2. The amplitude loss due to the SMA linear polarization was compensated by a constant gain of  $\sqrt{2}$ . We further corrected for DBE1 phase offsets. The optimal fringe fitting interval was 20 s, twice the shortest coherence time on APEX baselines.

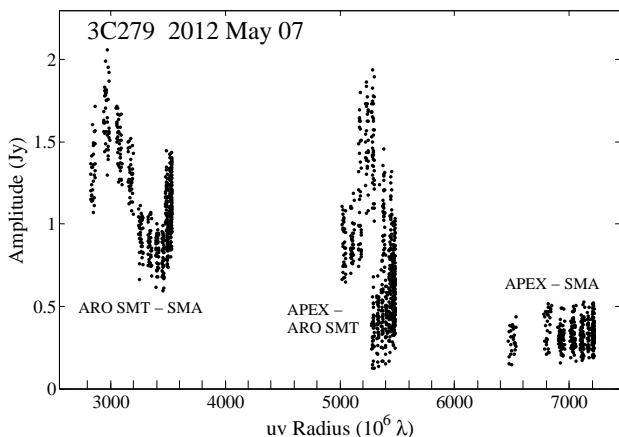


Fig. 2: Visibility amplitude (Jy) against uv distance ( $M\lambda$ ), averaged using an integration time per point of 10 s.

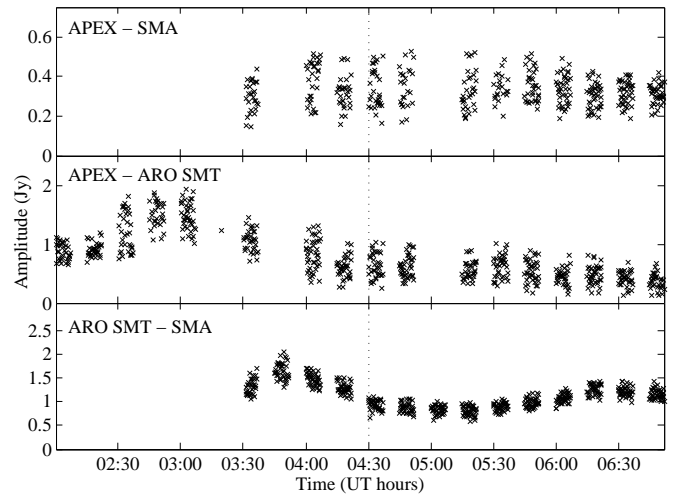


Fig. 3: Visibility amplitudes (Jy) against time, averaged to 10 s per point. The vertical line indicates the polarization swap on the APEX–SMT (LL to RR) and other baselines (LX to RX).

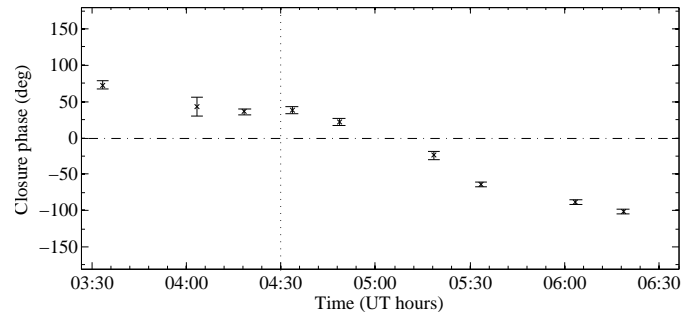


Fig. 4: The mixed polarization “closure phase” (top) with  $1\sigma$  uncertainties, averaged to 420 s per point. The vertical line indicates the time of polarization change from LLX to RRX.

#### 6. Results and Discussion

Strong fringes were detected on all VLBI baselines. The visibility amplitudes are shown against uv distance in Fig. 2, and against time in Fig. 3. The phased SMA measured a flux density of 19.8 Jy, agreeing well with the nearest data (2012 April 27, May 11) of their monitoring program (Gurwell et al. 2007). The backends at APEX yielded zero baseline correlation coefficients of  $> 0.95$ , demonstrating the DBBC to be ready for mm-VLBI.

The APEX–SMA and ARO SMT–SMA baselines produced mixed-hand fringes (LX, RX) with SNRs reported by the HOPS fringe fitter of between 12 and 35 in 420 s on the former baseline, and SNRs of up to 55 on the latter. The APEX–ARO SMT baseline produced parallel hand fringes (LL, RR) with SNRs between 12 and 35 in 420 s. No fringes were detected in the cross-hands (LR, RL). Assuming a detection threshold SNR of 6, this sets an upper limit of 20 % on the linear polarization fraction of 3C 279 fine-scale structure. This appears consistent with the nearest VLBA–BU–BLAZAR 43 GHz maps (2012 April 28, May 26) that show polarization degrees between 1 % and 14 % for three components detected in the inner 1 mas of 3C 279 (S. Jorstad, priv. comm.). For other 43 GHz images, see the VLBA–BU–BLAZAR web page or Jorstad et al. (2015, in preparation).

The mixed-polarization “closure phase” on the APEX–ARO SMT–SMA triangle (LLX, RRX) is shown in Fig. 4. The closure phase signature of a single source component is zero

<sup>3</sup><http://www.haystack.mit.edu/tech/vlbi/hops.html>

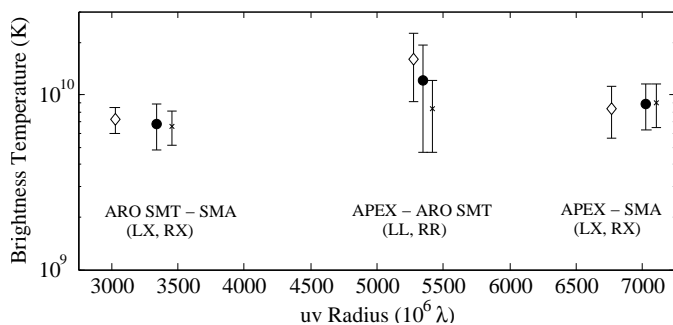


Fig. 5: Lower limits of the inner jet brightness temperature based on visibilities before (diamonds), after (crosses), or across (solid) the APEX polarization switch, with  $1\sigma$  uncertainties.

at all polarization fractions, independent of antenna polarization hands. The detection was not consistent with this signature. This implies two or more components, possibly polarized. Continuity in “closure phase” and visibility amplitudes across the APEX polarization swap (Figs. 3, 4) further suggests that any polarized sub-structure is only weakly polarized or almost point-like.

Model fitting to constrain the sub-structure is complicated by the mixed polarization setup. It may have corrupted visibilities on SMA baselines and source structure phase in the observed “closure phase”. These data contain the desired co-polar signal with well studied contaminants (e.g., Massi et al. 1996), as well as cross-polar contamination that is non-trivially dependent on instrumentation and polarized source structure. We simulated models of plausible 3C 279 fine-scale structure with different degrees of component polarization using AIPS task DTSIM, modified to generate mixed polarization visibilities. The closure phase corruption was found to be mostly small relative to the trend in Fig. 4. In contrast, the amplitudes on SMA baselines were impacted by larger polarization-dependent offsets and some parallactic angle -dependent variation. Robustly untangling source structure and contaminations in the observed mixed-polarization data proved challenging.

The APEX-ARO SMT visibilities (LL, RR) are unaffected by the SMA polarization. We thus follow a common approach used for sparse visibility data to derive a lower limit of the brightness temperature,  $T_b$ , of the inner jet region, based on visibility amplitudes,  $S(q)$ , against uv distance,  $q$  (see, e.g., Lobanov 2015). Two assumptions are necessary. Firstly, that visibility amplitudes are dominated by the radio core, and secondly, that the resolved structure is sufficiently well described by a circular Gaussian component ( $T_b = [2 \ln 2 / (\pi k_B)] S \lambda^2 / \theta^2$ ), with a full width at half maximum size,  $\theta$ . A fringe detection implies that  $\theta$  is smaller than the respective fringe spacing, i.e.,  $\theta \leq 1/q$ .

The resultant *lower limit* of  $T_b$  of the inner jet region is about  $10^{10}$  K. It is shown against uv distance in Fig. 5, with “lower limits” on SMA baselines shown for reference. Lastly, we note that *estimating* the  $T_b$  of the core, and identifying other inner jet -related fine-scale structure, requires future quasi-simultaneous VLBI imaging observations at 1.3 mm and longer wavelengths.

## 7. Conclusions

The first APEX 1.3 mm VLBI fringes with a longest baseline of 7200 M $\lambda$  and a shortest fringe spacing of 28.6  $\mu$ as demonstrated that new mm-VLBI observations can now be carried out with an improved angular resolution. For Sgr A\* and M 87 in particular a sufficiently high resolution can now be reached to directly probe the accretion physics and strong relativistic effects at event horizon scales. The current 3C 279 mixed-polarization

data at this unprecedented high resolution showed hints of fine-scale structure, but did not allow a detailed study. New 1.3 mm VLBI observations that include 3C 279 have been made (March 2013) with the largest array yet available at this frequency, now six stations including APEX. These new data are being analyzed.

## 8. Acknowledgments

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*Facilities:* APEX, SMA, ARO SMT.

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